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13. ABSTRACT (Maximum 200 words)  This project was undertaken to define the important unresolved issues involving snow and ice. The Terrestrial Sciences Program directed by Dr. Russell Harmon at the Army research Office has as one of its responsibilities the funding of research that will advance knowledge about snow and ice mechanics. In 1981 a workshop involving the properties of snow was sponsored jointly by NSF and ARO to determine the important unresolved problems. This workshop sponsored by this grant is the first since that time to again discuss the current state-of-the-art and to ask what are the important unresolved problems. The workshop was held October 3-6 1995 at the 320 Ranch near Bozeman, Montana and was divided into two parts, one to discuss ice and the other to address issues involving snow. The ice session was chaired by Dr. Erland Schulson of Dartmouth College, and the snow session was chaired by Dr. Robert L. Brown of Montana State University. Approximately 45 leading scientists and engineers from the United States and six other countries participated in the workshop. The findings were presented in a workshop report.				
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**Workshop on Future Directions in  
Snow and Ice Research**

**FINAL REPORT**

**Robert L. Brown**

**September 1, 1996**

**U.S. ARMY RESEARCH OFFICE**

**Grant No. 33621-GS-CF**

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## 1.0 PROBLEM STATEMENT

In 1981 a workshop on the properties of snow was jointly sponsored by the Army Research Office and the National Science Foundation. The workshop was held for the purpose of discussing and identifying the areas of study that had to that date not been adequately resolved. While prioritizing was not one of the primary objectives of the workshop, areas worthy of further study were identified and described in the workshop report.

The workshop discussed here, **"Future Directions in Snow and Ice Research"**, had a similar purpose. Rather than just considering research issues associated with snow, the topics of ice mechanics and ice physics were also addressed. The first two days were devoted to ice, while the last two days were concerned only with snow mechanics and snow physics. These two areas are certainly intertwined. For instance, most of the properties of snow are determined in part by the properties of ice. Conversely, most ice found on the earth formed from snow, and the long process of ice formation from snow is affected by the unique properties of snow. However, snow and ice represent a fairly clear cut division in terms of what researchers usually study, and interaction between snow researchers and ice researchers is limited. Consequently it was decided to treat these two areas separately.

The Army Research Office asked for this workshop for reasons associated with Army mission. The Terrestrial Sciences Program directed by Dr. Russell Harmon has responsibility for funding and coordinating research activity in snow, ice and permafrost. This funded research needs to be of such a nature that it can contribute to the Army mission. This workshop, therefore, was given the objective of defining those research areas consistent with Army mission. In addition we were asked to assess priority to each area of research. As a consequence, some areas of snow and ice research may indeed be of importance to a number of constituencies yet not be highly ranked as a result of this workshop. As an example, avalanche mechanics and avalanche hazard forecasting is a topic which is extremely important in Canada, Japan and Europe but is not ranked high on the priority list by the Army. In addition, properties of ice relating to glacier flow and the glacier bed problem may be of considerable importance but would not be highly prioritized in this workshop.

In recognition of the importance of ice to a variety of human activities, the workshop was recently convened. It was held on October 3 -6, 1995 at the 320 Ranch, Gallatin Gateway, Montana and sponsored by the Army Research Office. The workshop was chaired by R. L. Brown and E. M. Schulson and was attended by invited participants (Appendices 3 and 4), both from this country and abroad. The purpose was twofold: to review both the current state of knowledge and understanding of some aspects of the physics and mechanics of snow and ice; and to outline fruitful areas for future research.

## 2.0 RELEVANCE TO ARMY MISSION

Snow and ice represent areas of research that are very relevant to the Army mission. Operations in alpine and polar environments is strongly affected by low temperatures and the presence of snow and ice. Areas of interest include but are not limited to topics such as: vehicle mobility in snow-covered terrain, danger represented by avalanches, traction mechanics on snow and ice, ice forces on piers and other shoreline structures, visibility reduction due to blowing and drifting snow, use of ice for bridges across waterways, trafficability of snow roads and ice roads, and many other areas too numerous to list here.

This workshop was held for the expressed purpose of reviewing the progress that has been made during the past fifteen years, determining the unresolved problems relevant to the Army mission, evaluating if these problems can be solved in the near future, and prioritizing these research areas.

### 3.0 SUMMARY OF RESULTS

#### 3.1 SNOW SESSION

The organization of the snow session was designed to maximize discussion between participants. Rather than having each of the participants present their research and discuss its importance, it was decided to have only four review papers presented, followed by discussion groups to encourage as much discussion as possible. Areas of study in snow mechanics and physics was divided into four areas:

Dynamic and Quasi-static Properties of Snow

Thermodynamics of Snow

Optical and Electrical Properties of Snow

Instrumentation Needs for Field and Laboratory Studies

In each of these areas, leading nationally recognize scientists were asked to discuss progress that had been made during the last fifteen years. They were also asked to present their views on what are the important unsolved problems that need to be studied during the next ten-year period. The individuals who presented reviews were:

Hans Gubler:	Instrumentation Needs
Jerome Johnson:	Dynamic and Quasi-static Properties
Ted Arons:	Thermodynamics
Steve Warren:	Optical Properties
Robert Davis:	Electrical Properties

The discussion groups were also chaired by individuals who were internationally recognized as leaders. These included:

R. A. Schmidt:	Instrumentation Needs
Jim Dent:	Instrumentation Needs
Sam Colbeck:	Thermodynamics
Jeff Dozier:	Optical and Electrical Properties

Each discussion group was given at least two hours to deliberate and arrive at a set of conclusions. Following this, the discussion leader then presented the group's findings to a plenary discussion session, during which a final set of findings were reached.

The workshop report was organized in such a way that historical perspectives can be assessed. The reviewer extended abstracts were first presented to give the reader some appreciation for advances during the past fifteen years. Also included in these abstracts were the reviewers' own opinions

regarding important unsolved problems. These were then followed by summary statements prepared by the discussion leaders. These summaries reflected what was arrived at collectively by the workshop participants. Finally a summary statement by the organizer of the snow session, Robert L. Brown was presented.

### 3.2 ICE SESSION

Two plenary sessions were held. Ice physics was discussed during the first day, and ice mechanics during the first evening and throughout the second day. Each topic began with a review lecture, was followed by short pre-arranged presentations, and then by a round-table discussion. During the second evening, both ice physics and mechanics were considered again, in the interests of summarizing the work of the preceding days. Appendix 2 lists the program agenda. Unfortunately, Drs. Sodhi and Johnson could not attend owing to unexpected events; however their contributions were given by Ms. Richter-Menge and Dr. Schulson, respectively. For the same reason Dr. Paul Duval of Laboratoire de Glaciologie et Geophysique de l'Environnement, Grenoble, who had accepted an invitation to present the review lecture on ice mechanics, could not attend.

The Individuals who gave presentations in the ice physics session were:

Robert Whitworth	Ice Physics
Victor Petrenko	Ice Adhesion
Kazuhko Itagaki	Ice Friction
Ian Baker	Crystallographic Defects

The individuals who gave presentations in the ice mechanics session were

Mark Kachanov	Crack Mechanics
Vijay Gupta	Crack Nucleation
Harold Frost	Crack Kinetics
Mao Wu	Crack Interactions
Lorne Gold	Probability Distributions in Cracks
Wilfred Nixon	Crack Growth
David cole	Cyclic Loading
Erland Schulson	Failure under Multiaxial Loading
John Dempsey	Scale Effects
Richard Schapery	Constitutive Models
Roy Johnson	Ice-Structure Interaction
Devinder Sohdi	Breakthrough Loads
Lorne Gold	Bearing Capacity
Jackie Richter-Menge	Pack Ice Stresses
William Hibler, III	Laboratory/Large-Scale Concepts

The exact titles of the presentations are given in the Appendix 2. The chairs for the ice physics sessions were Erland Schulson and Harold Frost, while the chairs for the ice mechanics sessions were Robert Whitworth, Mark Kachanov, John Dempsey, and Russell Harmon.

## **4.0 PUBLICATIONS RESULTING FROM GRANT**

The workshop resulted with the report:

“Future Directions in Snow and Ice Research,” by Robert L. Brown and Erland  
M. Schulson

This report provided a determination and prioritization of the important unsolved problems in snow and ice. it is available from the Terrestrial Sciences Program at the Army Research Office.

## APPENDIX 1: Snow Session Agenda

### Day 3: Thursday

8:00 AM	Opening Welcome (Robert Brown, MSU, Russell Harmon, ARO)
8:30 AM	Plenary Talk: <b>Dynamic and Quasi-static Mechanical Properties</b> (Jerry Johnson)
9:15 AM	Plenary Talk: <b>Optical and Electrical Properties of Snow</b> (Steve Warren)
10:00 AM	Coffee Break
10:30 PM	Plenary Talk: <b>Thermodynamics of Snow</b> (Ted Arons)
11:15 PM	Plenary Talk: <b>Instrumentation Needs for Field and Laboratory Studies</b> (Hans Gubler)
12:00 PM	Instructions to Group Leaders (Robert Brown)
12:30 PM	Lunch
1:00 PM	Afternoon Break
5:00 PM	Social Hour
6:00 PM	Dinner
7:00 PM	Evening Sessions for Discussion Groups
	Group I: <b>Dynamic and Quasi-static Mechanical Properties</b> (Jim Dent, Chair)
	Group II: <b>Optical and Electrical Properties</b> (Jeff Dozier, Chair)
9:00 PM	Adjourn

### Day 4: Friday

8:00 AM	Plenary Discussion: <b>Dynamic and Quasi-static Mechanical Properties</b> (Jim Dent)
9:00 AM	Plenary Discussion: <b>Optical &amp; Electrical Properties</b> (Jeff Dozier)
10:00 AM	Coffee Break
10:30 AM	Session for Discussion Groups
	Group III: <b>Thermodynamics of Snow</b> (Sam Colbeck, Chair)
	Group IV: <b>Instrumentation Needs</b> (R. A. Schmidt, Chair)
12:30 PM	Lunch
1:30 PM	Afternoon Break
4:00 PM	Plenary Discussion: <b>Thermodynamics of Snow</b> (Sam Colbeck)
5:00 PM	Plenary Discussion: <b>Instrumentation Needs</b> (R. A. Schmidt)
6:00 PM	Social Hour
7:00 PM	Dinner
8:00 PM	Closing Session



## APPENDIX 2: Ice Session Agenda

Tuesday 3 October 1995

8:00            WELCOME AND INTRODUCTION  
                 Erland Schulson                    Russell Harmon  
                 Dartmouth College                Army Research Office

### SESSION 1: ICE PHYSICS

*Harold Frost, Thayer School of Engineering, Dartmouth College*

8:30            ICE PHYSICS: PROGRESS AND CHALLENGES  
                 Robert Whitworth, The University of Birmingham

9:15            ICE ADHESION  
                 Victor Petrenko, Dartmouth College

9:30            ICE FRICTION  
                 Kazuhiko Itagaki, CRREL

9:45            FROM CRYSTALLOGRAPHIC DEFECTS TO MECHANICAL  
                 BEHAVIOR OF ICE  
                 Ian Baker, Dartmouth College

10:00           COFFEE BREAK

10:30           GENERAL DISCUSSION ON PROBLEMS AND PRIORITIES IN ICE PHYSICS  
                 Robert Whitworth                    Ian Baker  
                 Discussion Leader                    Recorder

12:30           LUNCH

13:30           AFTERNOON FREE

18:00           DINNER

### SESSION 2: ICE MECHANICS

*Robert Whitworth, Chairman, The University of Birmingham*

19:00           SOME ASPECTS OF THE MECHANICAL BEHAVIOR OF MATERIALS  
                 WITH MULTIPLE CRACKS AND PORES OF VARIOUS SHAPES  
                 Mark Kachanov, Tufts University

11:15           A PERSPECTIVE ON LINKING LABORATORY AND LARGE-SCALE ICE  
                 MECHANICS CONCEPTS  
                 William D. Hibler, III, Dartmouth College

11:30           GENERAL DISCUSSION ON PROBLEMS AND PRIORITIES IN ICE MECHANICS  
                 George Ashton                               Roy Johnson  
                 Discussion Leader                       Recorder

12:30           LUNCH

- 19:45 THE NUCLEATION OF CRACKS IN ICE  
Vijay Gupta, UCLA
- 20:00 KINETICS OF CRACK FORMATION IN ICE  
Harold Frost, Dartmouth College
- 20:15 DISCUSSION
- 21:00 ADJOURN

Wednesday 4 October 1995

SESSION 2: ICE MECHANICS (continued)  
*Mark Kachanov, Chairman, Tufts University*

- 8:00 CRACK INTERACTIONS UNDER COMPRESSION  
Mao S. Wu, The University of Nebraska
- 8:15 PROBABILITY DISTRIBUTION OF CRACKS IN ICE  
Lorne Gold, NRC Canada
- 8:30 SUBCRITICAL CRACK GROWTH IN ICE  
Wilfrid Nixon, The University of Iowa
- 8:45 THE CYCLIC LOADING OF ICE: EXPERIMENTS AND MODELING  
David Cole, CRREL
- 9:00 THE FAILURE OF ICE UNDER MULTIAXIAL COMPRESSION  
Erland Schulson, Dartmouth College
- 9:15 SCALE EFFECTS ON FRACTURE AND CONSTITUTIVE BEHAVIOR OF ICE  
John Dempsey, Clarkson University
- 9:30 CONSTITUTIVE MODELS FOR ICE  
Richard Schapery, The University of Texas
- 9:45 COFFEE BREAK

SESSION 2: ICE MECHANICS (continued)  
*John Dempsey, Chairman, Clarkson University*

- 10:15 THE ICE-STRUCTURE INTERACTION PROBLEM  
Roy Johnson, Mobil Research and Development Corporation
- 10:30 BREAK-THROUGH LOADS OF FLOATING ICE SHEETS  
Devinder Sodhi, CRREL
- 10:45 BEARING CAPACITY OF AN ICE SHEET  
Lorne Gold, NRC Canada
- 11:00 CHARACTERISTICS OF PACK ICE STRESSES IN THE ALASKA BEAUFORT SEA  
Jackie Richter-Menge, CRREL

14:00            GENERAL DISCUSSION ON PROBLEMS AND PRIORITIES IN ICE MECHANICS  
(Continued)

16:00            FREE PERIOD

18:00            DINNER

SESSION 3:    SUMMARY OF PRIORITIES IN ICE RESEARCH  
*Russell Harmon, Chairman, Army Research Office*

19:00            ICE PHYSICS  
                 Robert Whitworth and Ian Baker

20:00            ICE MECHANICS  
                 Erland Schulson and Roy Johnson

21:00            ADJOURN

### APPENDIX 3: Attendees for Snow Session

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